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(54) A method of linearizing a flow velocity sensor and a linearized flow velocity measurement apparatus

(57) The invention relates to a method and apparatus for linearizing a flow velocity sensor based on pressure difference measurement. According to the method, such a difference of two pressure signals (4, 5) is measured from the flow under measurement that is proportional to the square of the flow velocity, the difference of said two pressure signals (4, 5) is measured using a micromechanically manufactured symmetrical capacitive differential pressure sensor (20) based on the force balance principle, in which sensor the pressure-induced deviation from force balance is compensated for by inducing on the pressure-sensing diaphragm (23) of said differential pressure sensor (20) a force-balance-restoring electrostatic pressure so that the pressure-sensing diaphragm (23) is subjected to the force-balance-restoring electrostatic force, whereby the amplitude of the force-balance-restoring electrical feedback control signal, which also acts as the system output signal, is directly proportional to the square root of said difference of said two pressure signals, and thus, a linear function of the flow velocity. According to the invention, said feedback control voltage depending on the direction of the pressure difference is applied only to either of the stationary electrodes (21 or 22) disposed on the same side relative to the sensing diaphragm so that the electrostatic force of attraction thus induced acts counter to the force generated by the pressure difference under measurement, whereby the polarity of the system output voltage signal is dependent on the direction of the flow.

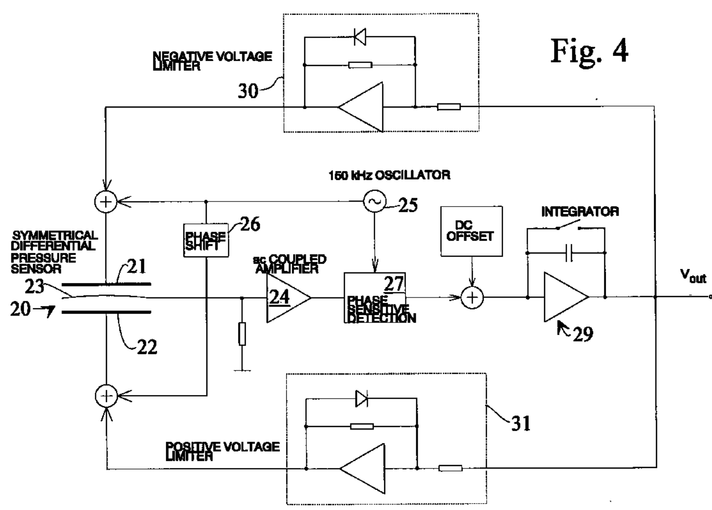

Fig. 4

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Description

The present invention relates to a method according to the preamble of claim 1 for linearizing a flow velocity sensor.

The method also concerns a linearized flow velocity measurement apparatus.

In the flow velocity measurement ofgases, the principle of major importance is to measure from the flow a variable called the dynamic pressure which is proportional to the square of the flow velocity. The simplest primary device of this kind is the Pitot tube having two pressure passages for measuring from the flow the kinetic pressure, also called dynamic pressure, which is the difference of total pressure and static pressure. The pressure difference between the openings of the Pitot tube can be expressed by the following formula:

$$\Delta p = \frac{1}{2}\rho \cdot q_{flow}^2 \qquad (1)$$

where ρ is gas density and q_{flow} is flow velocity.

In general, the quadratic form of the equation results from the Bernoulli equation which is a basic formula depicting the dynamics of the flow. For a noncompressible, friction-free flow the above formula can be written in the following form:

$$\frac{p}{\rho}+gh+\frac{q_{flow}^2}{2}=constant \qquad (2)$$

where g is constant of gravitational acceleration and h is elevation of the pressure ports relative to a given reference level. The equation is valid along any point of a flow line. Flow velocity meters based on Bernoulli's law are available in a variety of different types. The two most important of primary devices in such meters are the Pitot tube and the Venturi, the latter using restriction of flow. The above-described quadratic relationship of the pressure difference also occurs in turbulent flow. Such flow velocity sensors are characterized by the common property that pressure is measured as a pressure differential between two different points of the sensor for the determination of the flow velocity.

However, the quadratic flow velocity-pressure differential relationship in these sensors essentially deteriorates the resolution of measurement when signal conversion is performed using an A/D converter whose resolution is relatively small, e.g., 8 bits.

Known from DE patent application 40 25 883 is an embodiment in which the flow velocity sensor is linearized by means of a capacitive force balance transducer. No sensing method of flow direction is disclosed in the patent publication.

It is an object of the present invention to overcome the disadvantages of the above-described techniques and to provide an entirely novel type of method for linearizing a flow velocity sensor with a particular property of flow direction indication and a linearized, bidirectionally measuring flow velocity measurement apparatus.

The goal of the invention is achieved by virtue of controlling the pressure-sensing diaphragm of a symmetrical capacitive differential pressure sensor into the undeflected position by means of an electrical feedback arrangement, whereby the feedback circuit establishing the force balance state of the sensor performs linearization of the inherently nonlinear pressure sensor output and simultaneously indicates the direction of flow. Advantageously such a pressure sensor is made using silicon micromechanical techniques.

More specifically, the method according to the invention is characterized by what is stated in the characterizing part of claim 1.

Furthermore, the apparatus according to the invention is characterized by what is stated in the characterizing part of claim 6.

The invention offers significant benefits.

The invention facilitates linear, bidirectional measurement of flow velocity. Also the resolution of flow velocity measurement is improved. Referring to Fig. 10, a graph is shown therein illustrating the output signal response of the linear-flow electronics according to the invention and a conventional electronics circuitry having a linear transfer function with respect to the pressure differential. Particularly at small values of flow velocity, the embodiment according to the invention offers a clearly improved output resolution in bidirectional measurement.

The output signal of the electronics circuitry according to the invention is insensitive to variations in supply voltage and other nonideal conditions. The output signal range is determined by the sensor properties.

In the following the invention will be examined in greater detail with reference to exemplifying embodiments illustrated in the appended drawings in which

Figure 1 is a longitudinally sectional side view of a conventional Pitot tube type of primary device;

Figure 2 is a longitudinally sectional side view of a conventional Venturi tube type of primary device;

Figure 3 is a block diagram of an embodiment of an electronics circuitry suited for unidirectional flow measurement with a differential pressure sensor, whose signal is conditioned for a linear response of the flow velocity measurement at the circuit output;

Figure 4 is a block diagram of an embodiment according to the invention of an electronics circuitry suited for bidirectional flow measurement with a differential pressure sensor, whose signal is conditioned for a linear response of the flow velocity measurement at the circuit output;

Figure 5 is a block diagram of a complete system suited for an application of the method and apparatus according to the invention;

Figure 6 is a graph illustrating the output voltage of an electronics circuitry for of unidirectional measurement according to the invention as a function of the differential pressure when the spacing of the measuring capacitor openings in the sensor is 0.5 µm;

Figure 7 is a graph illustrating the output voltage an electronics circuitry for bidirectional measurement according to the invention as a function of the differential pressure when the spacing of the measuring capacitor openings of the sensor is 0.5 µm;

Figure 8 is a graph illustrating the output voltage of the apparatus according to the invention as a function of flow velocity;

Figure 9 is a graph illustrating the output voltage of the apparatus according to the invention and corresponding flow velocity as a function of time;

Figure 10 is a graph illustrating the output voltage of the apparatus according to the invention and a sinewave differential pressure input signal as a function of time;

Figure 11 is a graph illustrating the output voltage of the apparatus according to the invention as a function of a large-amplitude sinewave differential pressure input signal oscillating at 1 Hz; and

Figure 12 is a graph showing a comparison of the output voltage-flow velocity relationship for a conventional apparatus with an apparatus according to the invention.

When an electric potential difference U is applied between the two electrodes of a capacitor, an electrostatic pressure appears on the surface of the electrodes with a magnitude expressed by the formula:

$$p_{electric} = \frac{\varepsilon \cdot U^2}{2 \cdot g^2} \quad (3)$$

where ε is the dielectric coefficient of the gaseous medium between the capacitor electrodes and g is distance between the capacitor electrodes. If the profile of the pressure-sensing diaphragm of the differential pressure sensor is kept nondeflected by means of an electrical feedback arrangement, the force balance state of the sensor is expressed by the formula:

$$\Delta p_{Pitot} = p_{electric} \quad (4)$$

Then, the function expressing the relationship between the feedback voltage signal, that is, the output voltage of the electronics circuitry and the flow velocity is linearized as expressed by the formula:

$$U = \sqrt{\frac{g^2 \cdot \rho}{\varepsilon}} \cdot q_{flow} \quad (5)$$

As shown in Fig. 1, a typical application environment for the invention is, e.g., a Pitot tube 1 with its measuring orifice 3 oriented against the flow. The static pressure is obtained from a reference pressure opening 2 and both pressures are taken to outlet ports 4 and 5 for pressure difference measurement. The pressure difference between the outlet ports 4 and 5 is proportional to the square of the flow velocity.

Now referring to Fig. 2, an alternative primary device is a Venturi tube 45 in which the flow passes from inlet opening 40 to outlet opening 41. Flow velocity is determined by measuring pressure difference between pressure outlets 42 and 43, whereby one pressure outlet 43 is placed in the restricted section 44 of the tube, while the other pressure outlet 42 is in the nonrestricted section of the tube.

Referring to Fig. 3, the key component in the measurement apparatus is a capacitive differential pressure sensor 6. The sensor element is comprised of at least one stationary electrode which in the illustrated case is divided into two separate electrodes 7 and 8, and of a pressure-sensing conducting diaphragm 9 forming the counterelectrode in the capacitive sensor 6. Shown in Fig. 3 is also a simple exemplifying circuit configuration capable of electronically implementing the quadratic feedback function. In principle, the circuit is comprised of two overlapping blocks, namely, a measurement block 10 which detects the capacitance (charge) of the sensor and a feedback block 11 whose function is to keep the sensor capacitance unchanged. In practice this means that the charge of the sensing diaphragm of the capacitive sensor 6 is kept constant by feedback control. In the two-electrode capacitor configuration shown in the diagram, signals in opposite phases are applied to electrodes 7 and 8 by means of a circuit block comprising an oscillator 14 and a phase inverter 15. Capacitors 16 block signals with frequencies lower than the measurement carrier signal from passing to the electrodes 7 and 8. If the net charge over one cycle of the measurement carrier signal applied to the electrode of the diaphragm 9 is zero, the sensor 1 is in force balance and no signal is passed to the high-pass filtered input of amplifier 12. In other words, while the electrode of diaphragm 9 in the force balance state may carry a static charge or its charge may vary at a low frequency charge, the measurement block 10 detects charge changes occurring at the measurement carrier frequency only. If the diaphragm 9 of the sensor 6 is forced to deflect, a charge component varying at the measurement carrier frequency will be imposed on the capacitor electrode of the diaphragm 9, whereby an AC signal will be passed to the input of amplifier 12. This signal is rectified and low-pass filtered in a phase-sensitive amplifier 13 and passed therefrom to the input of integrator 17. The output signal of the integrator 17 is applied as a feedback signal to the electrode of diaphragm 9 of sensor 6 thus opposing its flexure. The feedback signal generates an electrostatic force of attraction between the moving electrode of the sensing diaphragm 9 and the stationary electrodes 7 and

8. In the force balance state the output signal of integrator 17 is simultaneously also a measurement signal with a linear response to the flow velocity. In practice, the attraction force generated by the measurement carrier signal causes a small offset error, which may be compensated for by the offset adjustment of the integrator 17.

Referring to Fig. 4, an embodiment of an electronic measurement circuit configuration is shown capable of using a symmetric differential pressure sensor 20 for bidirectional flow velocity measurement so that a linear output signal response vs. flow velocity is achieved. A symmetrical differential pressure sensor 20 comprises a stationary top electrode 21, a stationary bottom electrode 22 and a conducting sensing diaphragm 23 which is arranged to deflect under applied pressure and is disposed between the stationary electrodes so as to form the center electrode of the sensing capacitor. It should be noted that the directional references (top and bottom) made above are related to the orientations of the diagram only. In practice, the sensor 20 may be mounted in any position. Analogously with the embodiment shown in Fig. 3, also the embodiment illustrated in Fig. 4 is based on measuring the net charge imposed by the measurement carrier signal on the electrode of the diaphragm 23 of the sensor 20 and controlling said net charge to a zero value in order to keep the profile of the diaphragm 23 exactly constant, advantageously flat. If the net charge imposed by the measurement carrier signal deviates from the zero value, an input signal will be applied to the amplifier 24 and amplified therein. The input signal results from the measurement carrier signal applied from oscillator 25 to the top electrode 21 and the bottom electrode 22 only if the phase-inverted carrier signals impose a nonzero net charge on the moving electrode of the diaphragm 23. A phase inverter 26 is used to apply the measurement carrier signal in opposite phase on the bottom electrode 22 with respect to the measurement carrier signal applied on the top electrode 21. The sensor output signal resulting at the carrier frequency in a deflection state of the diaphragm deviating from force balance will be rectified and low-pass filtered in a phase-sensitive detector 27, if necessary offset-corrected by offset correction circuit 20 and taken to the input of an integrator 29. The feedback force can be generated bidirectionally depending on the polarity of the output signal of integrator 29. Hence, depending on the output signal polarity of the integrator 29, the feedback signal is applied with the help of limiter circuits 30 and 31 only to either of the stationary electrodes 21 and 22 of the sensor. The limiter circuits 30 and 31 comprise, e.g., an operational amplifier with a resistor and a diode parallel connected on its feedback loop. For example, if the sensing diaphragm 23, which is taken to the ground potential, tends to deflect downward under pressure, the feedback circuit applies a positive voltage to the top electrode that pulls the sensing diaphragm 23 into a position in which the net charge on the diaphragm electrode 23 is controlled to zero, whereby the force balance state of the system is restored. Thus, the output of integrator 23 provides a voltage signal which is a linear function of flow velocity. If so desired, the electrodes 21 and 22 may be divided into two or more subelectrodes as shown in Fig. 3.

Referring to Fig. 5, the arrangement shown therein has both a primary device 50 (e.g., a Pitot or Venturi tube) for flow velocity measurement and a flow-restricting control plate 61 disposed in a flow pipe 62. The pressures from the two outlet ports 55 and 56 of the flow velocity sensing primary device are connected to a differential pressure sensor 51, in which the position signal 58 of the pressure sensing diaphragm of the sensor is detected by means of a measurement and control circuit block 52, and according to the detected deflection of the sensing diaphragm, the diaphragm position is feedback-controlled 59 by applying an electrostatic force of attraction to one side of the sensing diaphragm only as earlier discussed in conjunction with the description of Figs. 3 and 4. From the control circuit 52, the output voltage signal 64 which also acts as the feedback control signal is taken to an A/D converter 53, whose digital output signal 63 is further taken to a microprocessor 54 adapted to control the flow rate in the flow pipe. For this purpose, the microprocessor 54 further steers a control plate 61 adapted to restrict the total flow rate in the flow pipe 62. Such a system may be applied to air-conditioning equipment, for instance. Other input signals to the flow-controlling microprocessor 54 may be, e.g., air temperature, relative humidity or concentration of a desired gas component.

Instead of the DC feedback configuration described above, the arrangement according to the invention may alternatively use a pulsed amplitude-modulated feedback circuit configuration.

In a preferred embodiment of the invention, a non-symmetrical pressure sensor 6 intended for use in the system has a design in which the stationary electrodes 7 and 8 have at least approximately equal surface areas. Furthermore, also the stationary electrodes 21 and 22 of a symmetrical pressure sensor 20 may be divided into two subelectrodes with approximately equal surface areas.

In Figs. 4 - 10 are shown graphs illustrating the performance of the embodiment according to the invention.

In the graph shown in Fig. 11, the ill-defined behaviour of the graph about the origin of the graph is related to a system transfer function singularity point at infinity.

Claims

1. A method of linearizing a flow velocity sensor based on pressure difference measurement, in which method

   - such a difference of two pressure signals (4, 5) is generated from the flow under measurement that is proportional to the square of the flow velocity, and

- the difference of said two pressure signals (4, 5) is measured using a micromechanically manufactured symmetrical capacitive differential pressure sensor (20) based on the force balance principle, in which sensor the pressure-induced deviation from force balance is compensated for by inducing a force-balance-restoring electrostatic pressure acting on the pressure-sensing diaphragm (23) of said differential pressure sensor (20) so that the pressure-sensing diaphragm (23) is subjected to the force-balance-restoring electrostatic force, whereby the amplitude of the force-balance-restoring electrical feedback control signal, which also acts as the system output signal, is directly proportional to the square root of said difference of said two pressure signals, and thus, a linear function of the flow velocity, **characterized** in that

- depending on the direction of the pressure difference, said feedback control voltage is applied only to either of the stationary electrodes (21 or 22) disposed on the same side relative to the sensing diaphragm so that the electrostatic force of attraction thus induced acts counter to the force induced by the pressure difference under measurement, whereby the polarity of the system output voltage signal is dependent on the direction of the flow.

2. A method as defined in claim 1, **characterized** in that the force balance principle is implemented feeding the pressure measurement sensor (20) with an AC measurement signal, measuring the pressure-induced change of charge on the sensing diaphragm (23) and feedback-controlling the position of the sensing diaphragm (23) by means of the applied electrostatic force of attraction to a position in which said change of charge induced by the AC measurement signal on said sensing diagram (23) is minimized.

3. A method as defined in claim 1, **characterized** in that said feedback control is implemented with the help of a DC signal applied between said conducting sensing diaphragm (23) and at least one stationary electrode (7, 8).

4. A method as defined in claim 1, **characterized** in that said feedback control is implemented with the help of an amplitude-modulated pulsed signal applied between said sensing diaphragm (23) and at least one stationary electrode (21 or 22).

5. A method as defined in claim 1 or 4, **characterized** in that at least two stationary electrodes (7, 8) are used on the same side of the pressure-sensing diaphragm (9) and that said electrodes are fed with pulsed signals of opposite polarities.

6. A linearized flow velocity measurement apparatus, comprising

- a flow velocity sensor (1) suited to be disposed in the flow under measurement, said sensor having two pressure outlet ports (4, 5) such that their pressure difference is proportional to the square of the flow velocity, and

- a micromechanically manufactured symmetrical capacitive differential pressure sensor (6) based on the force balance principle, in which sensor the applied feedback control signal is proportional to the square root of said pressure difference between said two pressure outlet ports (4, 5) and which sensor is capable of converting said pressure difference between said pressure outlet ports (4, 5) into and electrical variable,
characterized in that

- the feedback control voltage generating circuitry comprises limiter circuits (30, 31) for applying the feedback control voltage to the stationary electrode or electrodes (21, 22) disposed on the same side relative to the sensing diaphragm so that the signal is applied one electrode at a time only.

7. An apparatus as defined in claim 6, **characterized** in that said apparatus comprises means (14, 15) for feeding the pressure measurement sensor (6) with an AC measurement signal, means (12, 13) for measuring the pressure-induced change of charge on the sensing diaphragm (9) and feedback control means (17) for feedback-controlling the sensing diaphragm (9) into a stable position in which said change of charge induced by said measurement signal on said sensing diagram is minimized.

8. An apparatus as defined in claim 6, **characterized** in that said feedback control circuitry is capable of applying a DC control voltage between said sensing diaphragm (9) and said stationary electrode(s).

9. An apparatus as defined in claim 6 or 7, **characterized** in that said feedback control circuitry is capable of applying a pulsed amplitude-modulated control voltage between said sensing diaphragm (23) and said stationary electrode(s) (21 or 22).

10. An apparatus as defined in claim 6, **characterized** in that a nonsymmetrical pressure sensor structure (20) is used having two stationary electrodes disposed to opposite sides relative to said conducting sensing diaphragm (23).

11. An apparatus as defined in claim 6, **characterized** in that a symmetrical pressure sensor structure (6) is used having two stationary electrodes (7, 8) disposed to the same side relative to said sensing diaphragm (9).

12. An apparatus as defined in claim 10 or 11, **characterized** in that the surface areas of said stationary electrodes (7, 8) are at least essentially equal.

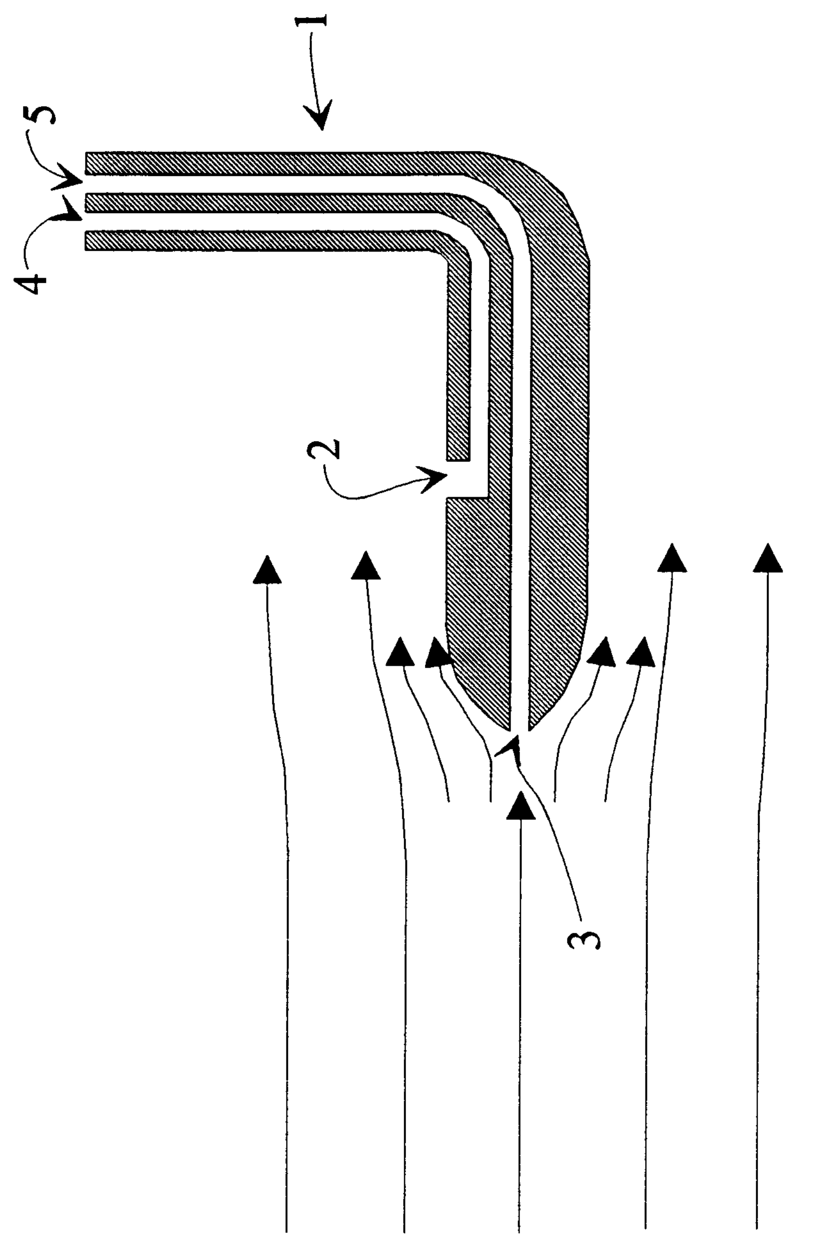


Fig. 1

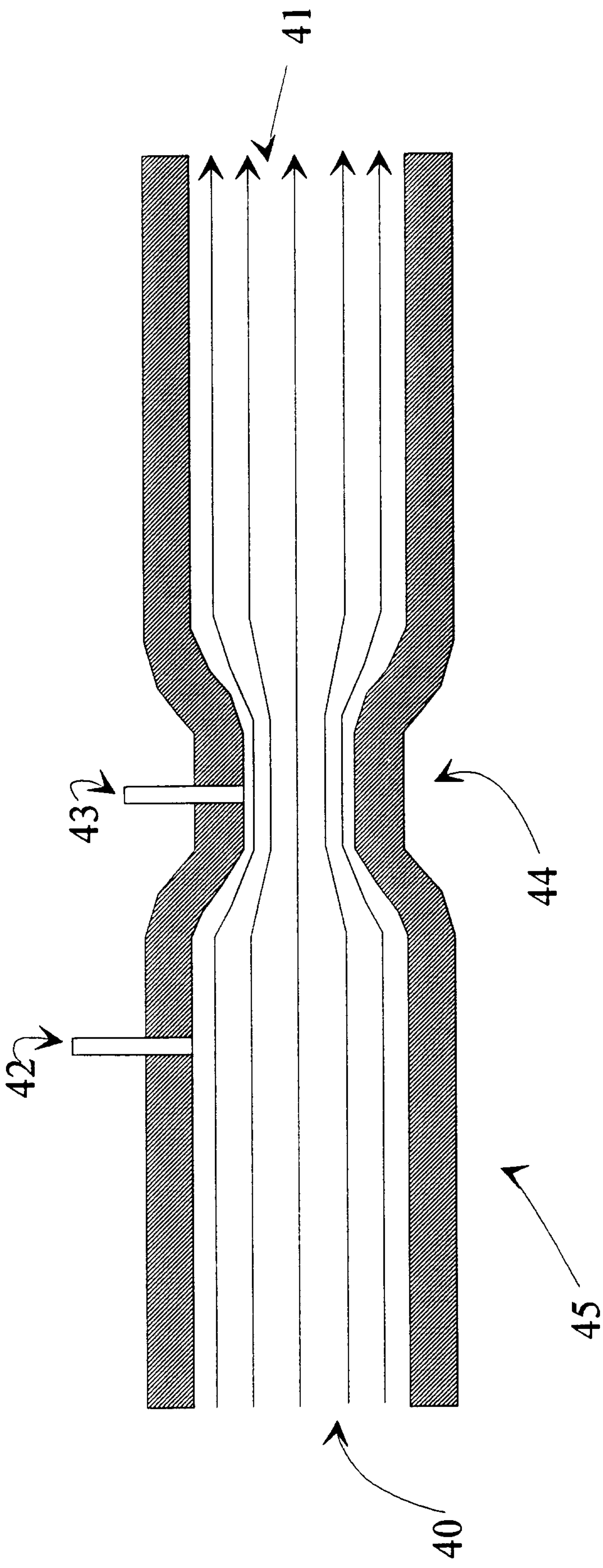
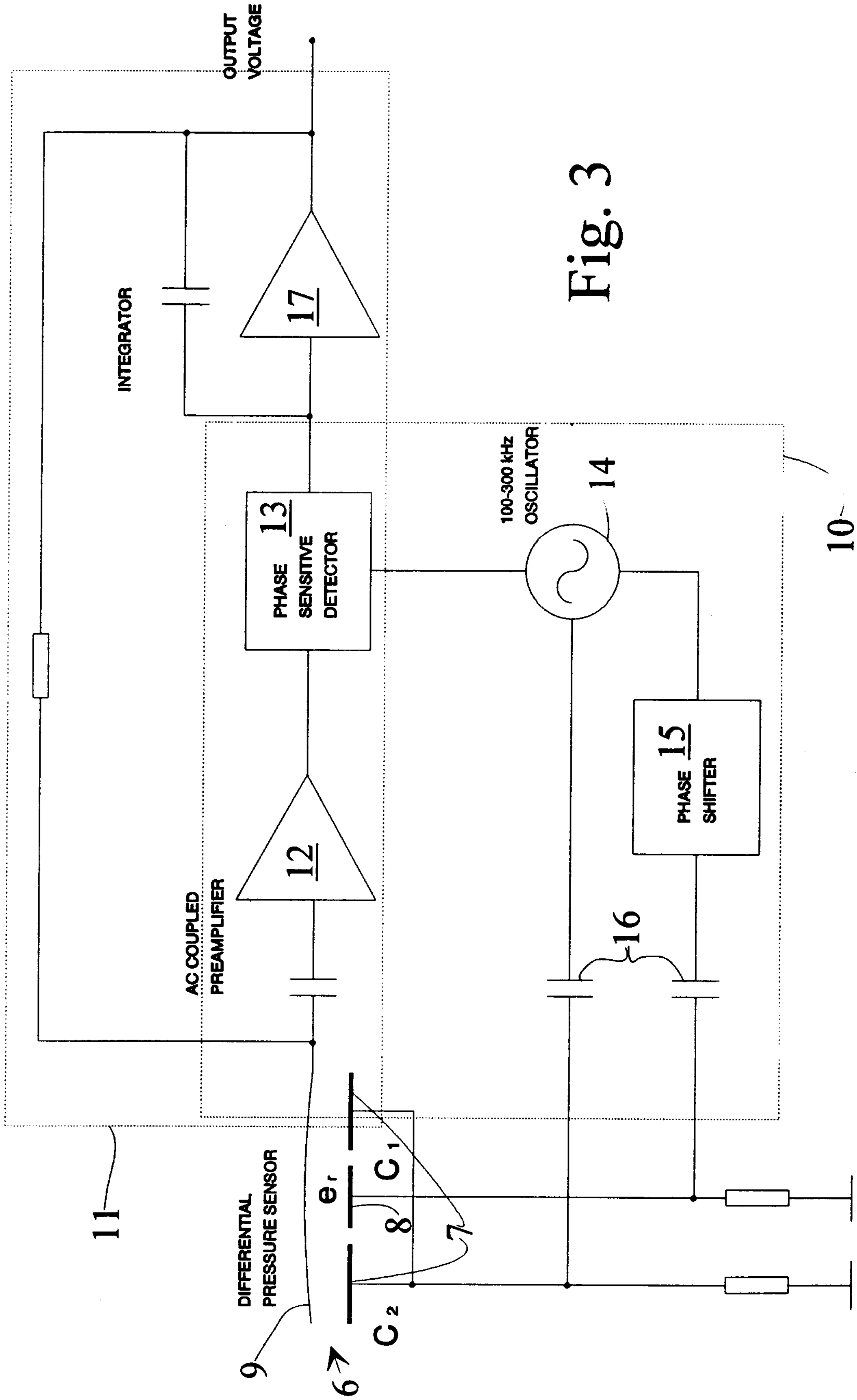


Fig. 2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13
100-300 kHz OSCILLATOR
14
10
AC COUPLED PREAMPLIFIER
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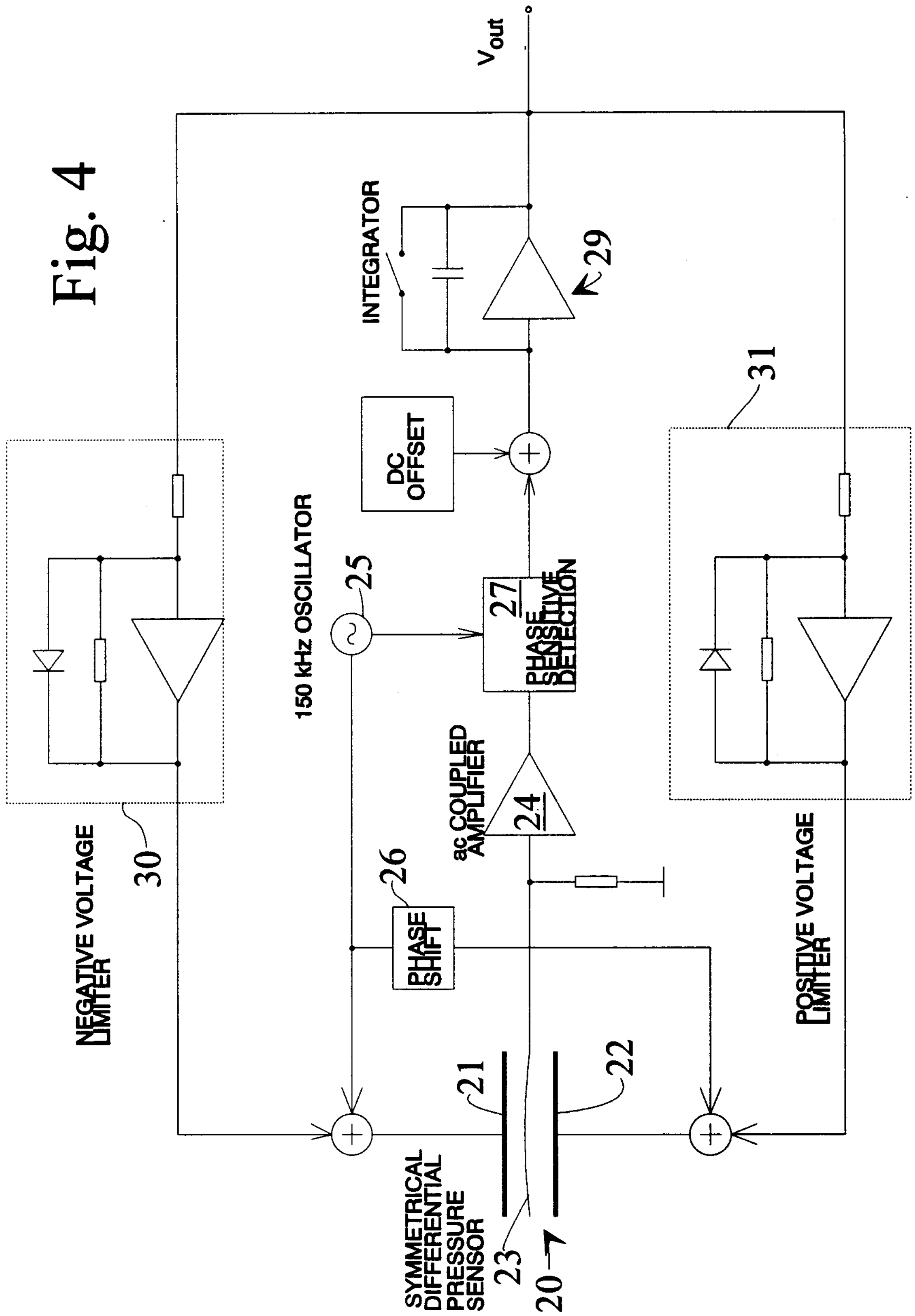
C 2
8
7
9
6

Fig. 3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NEGATIVE VOLTAGE LIMITER
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PHASE SHIFT
POSITIVE VOLTAGE LIMITER
21
22
SYMMETRICAL DIFFERENTIAL PRESSURE SENSOR
23
20

Fig. 4

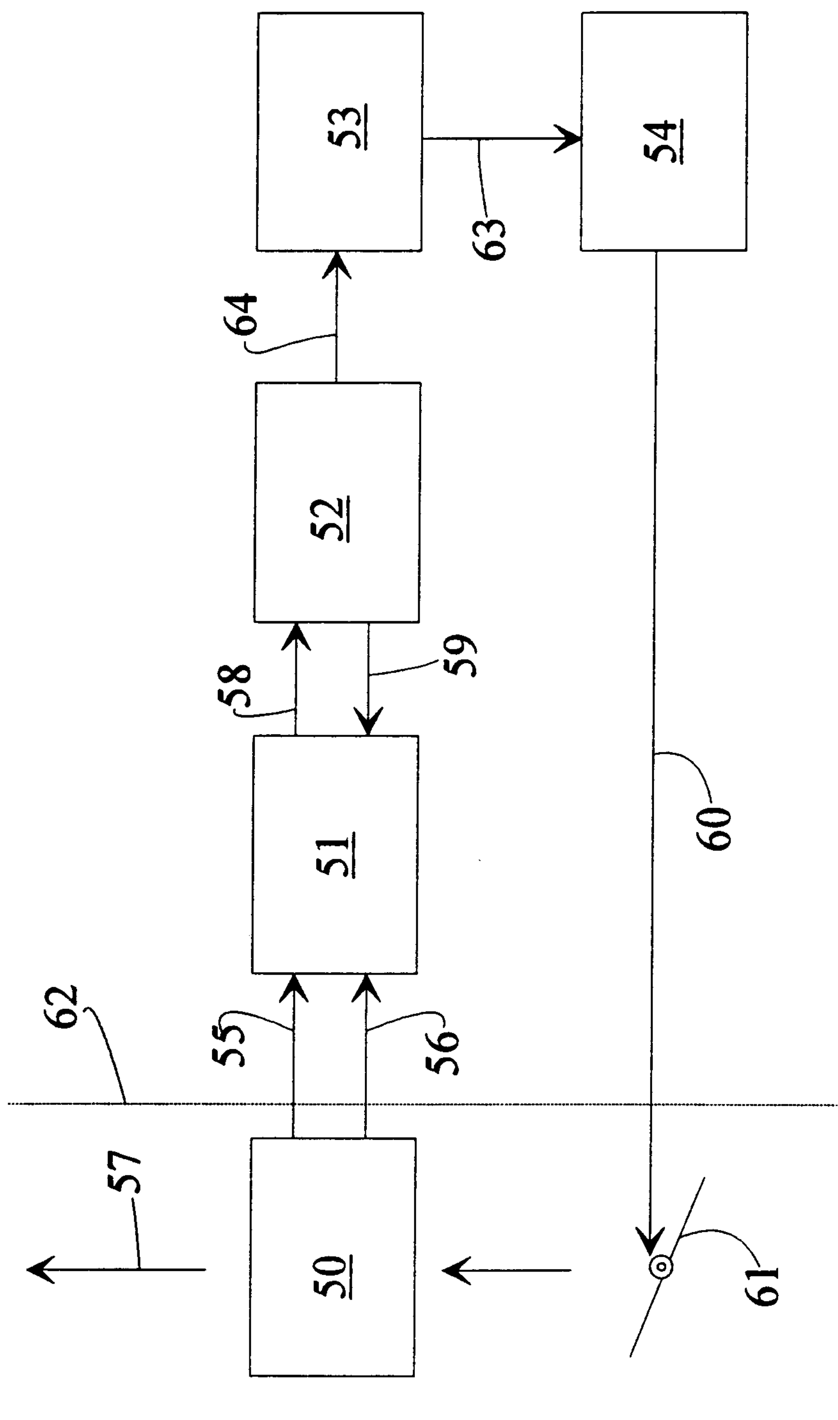

Fig. 5

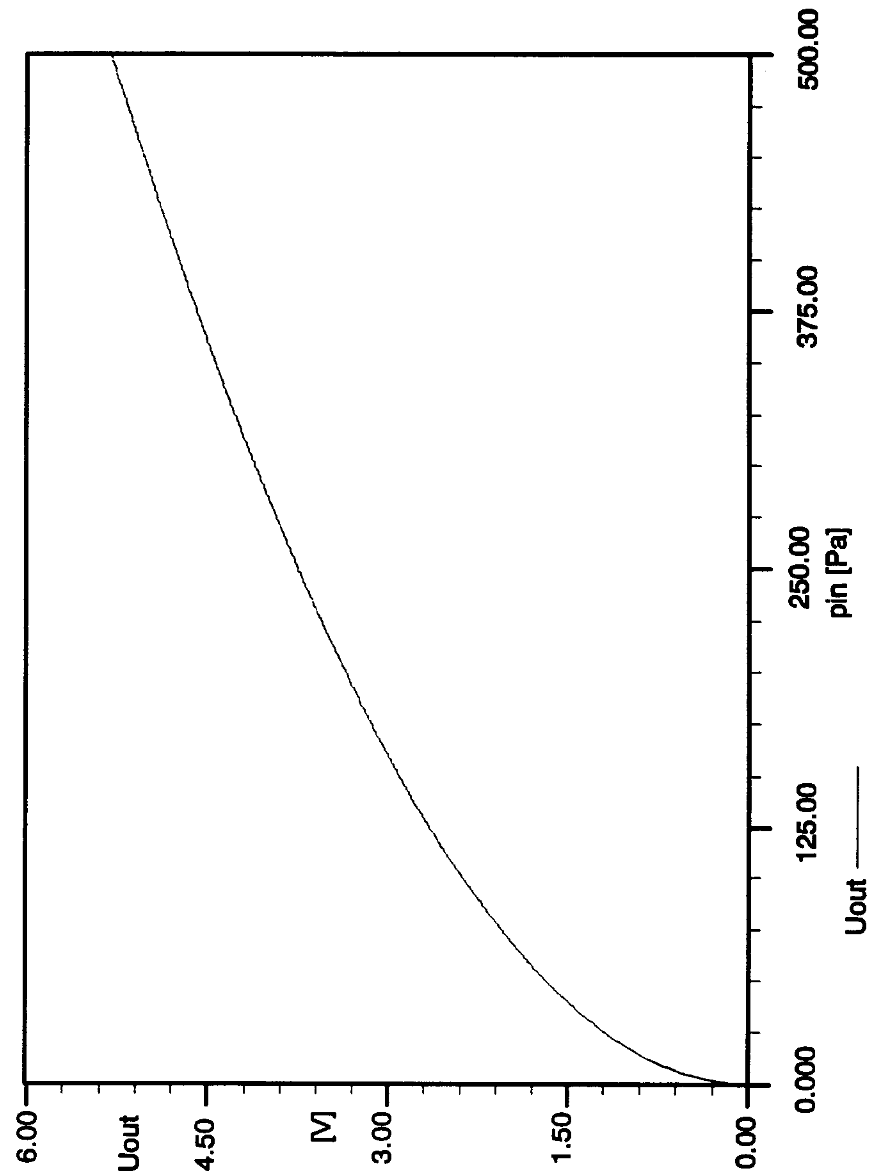
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Fig. 6

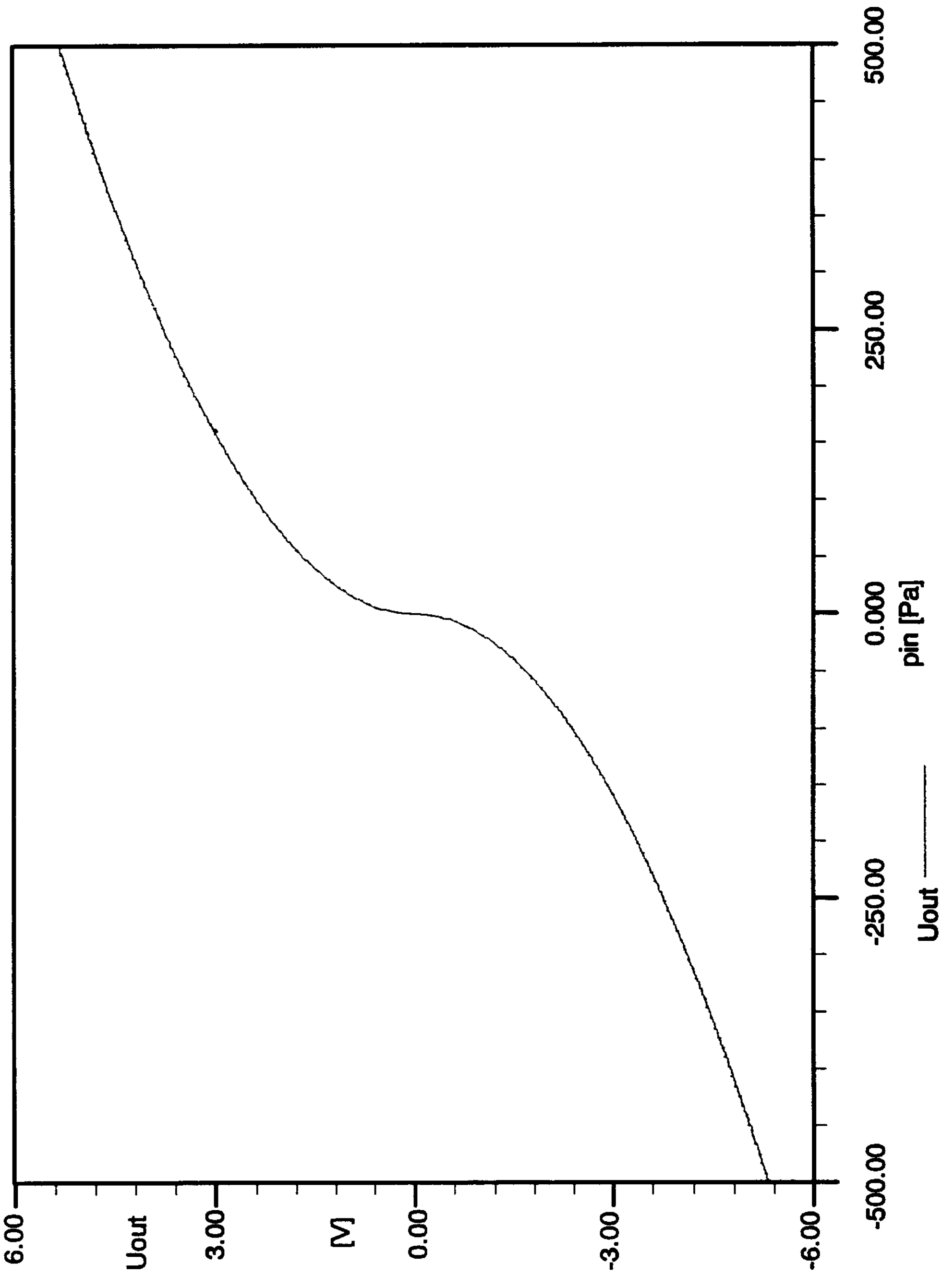
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Fig. 7

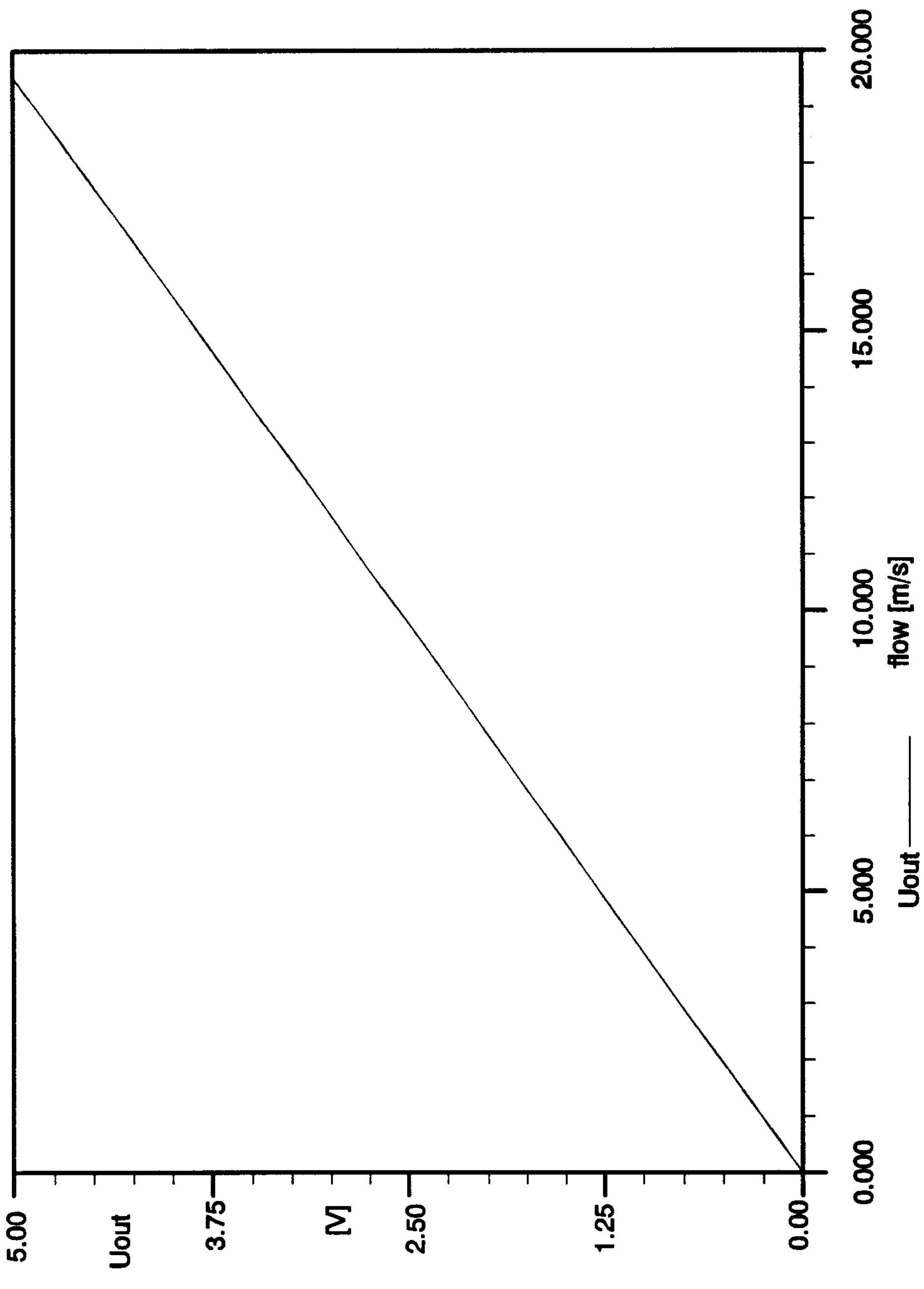
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Fig. 8

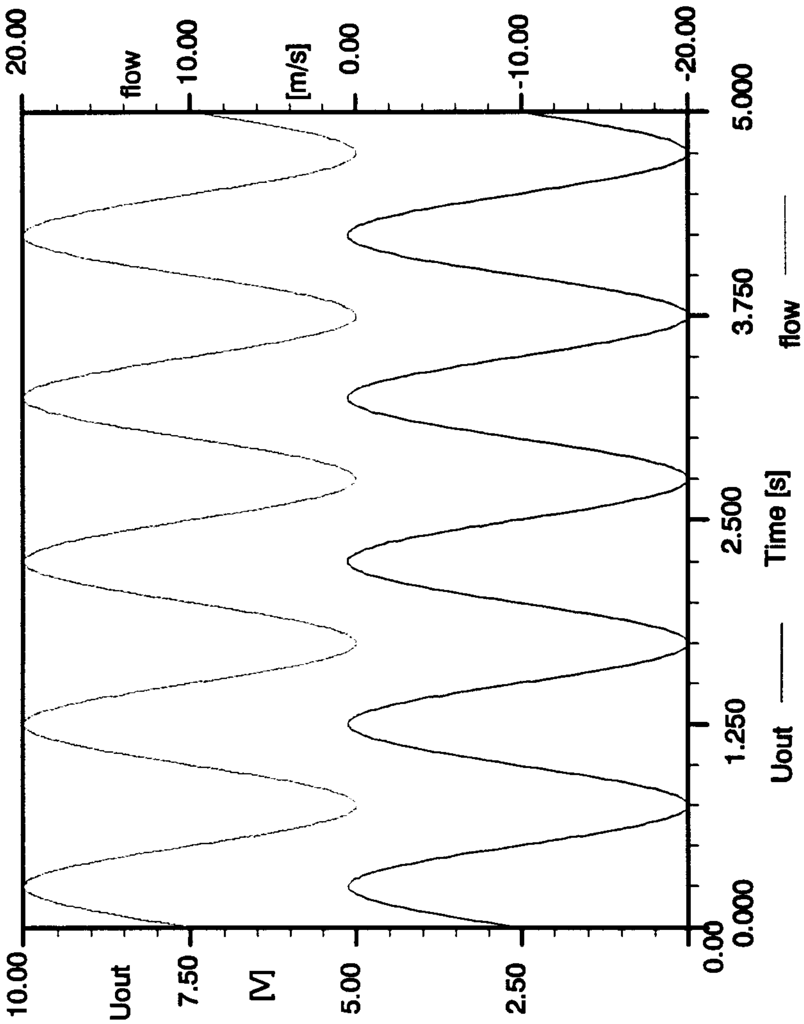
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Fig. 9

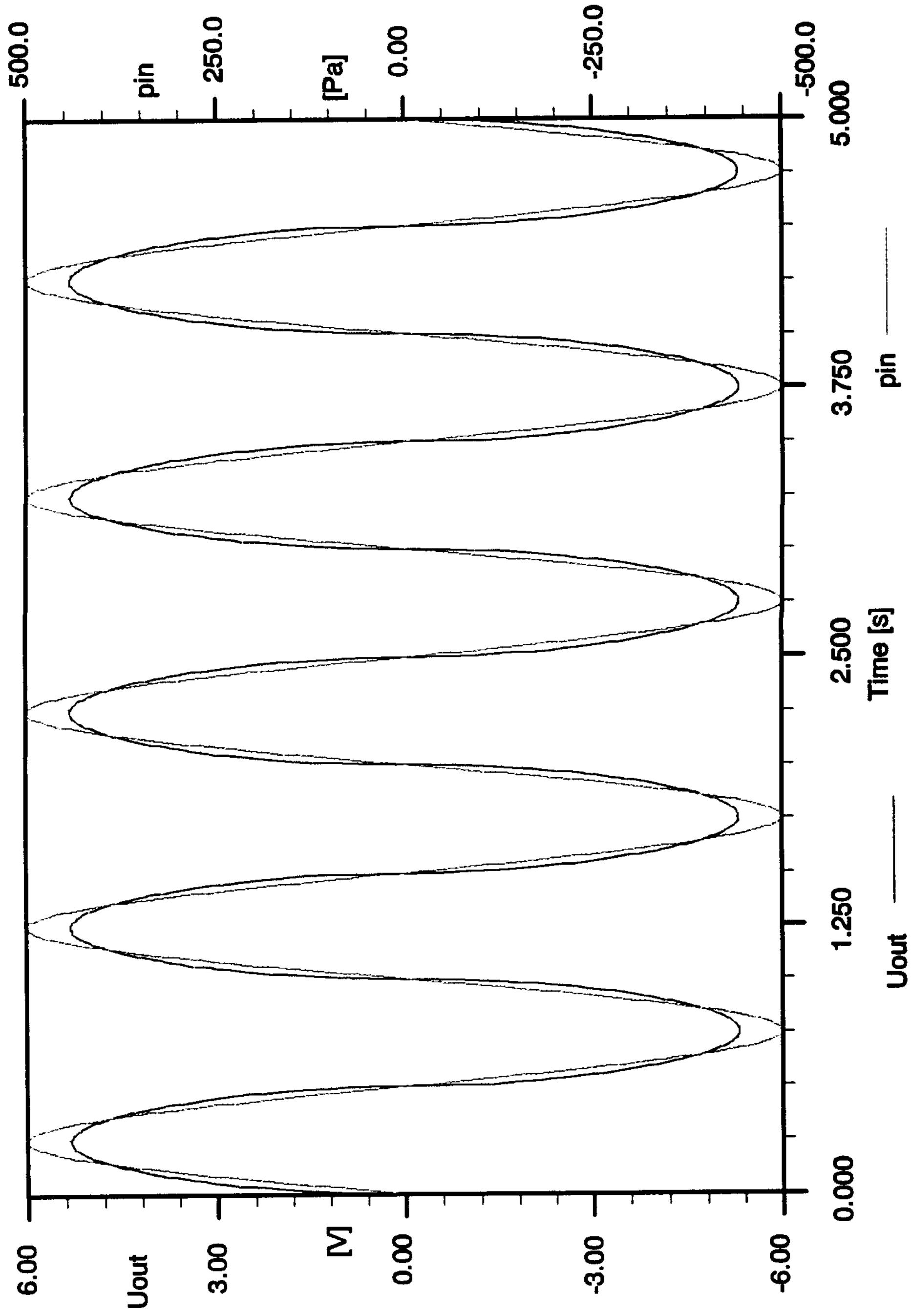
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Fig. 10

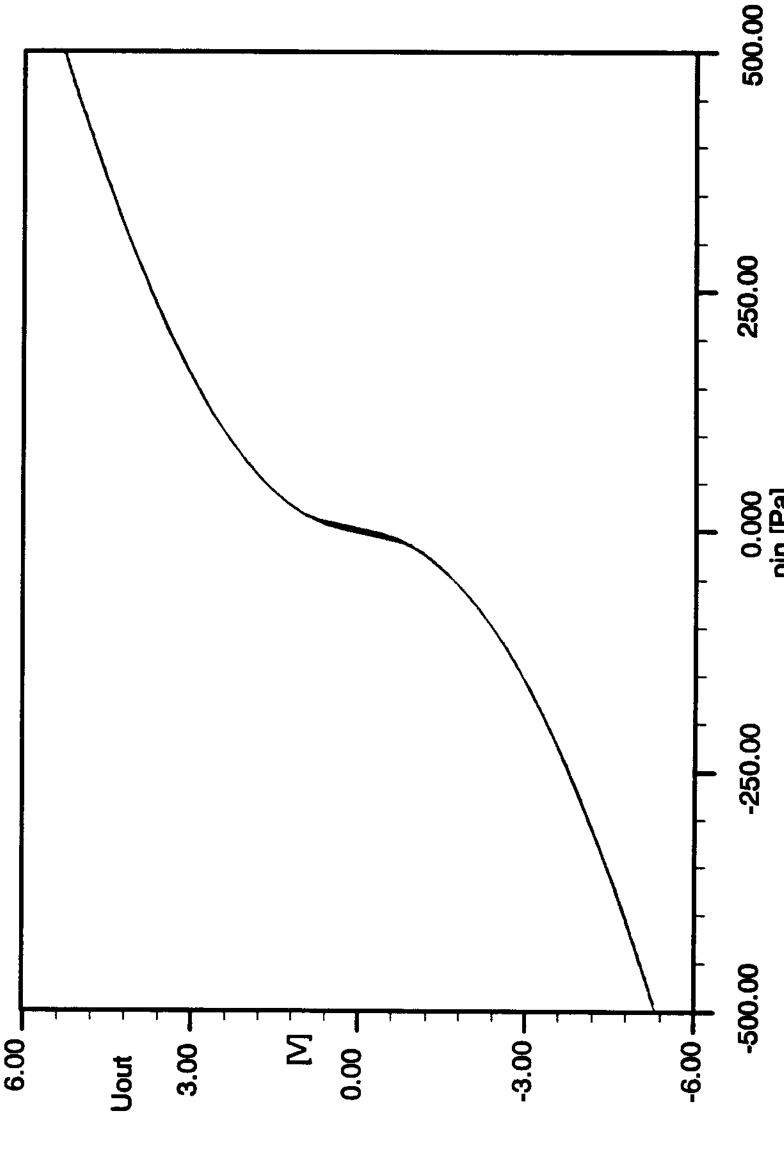
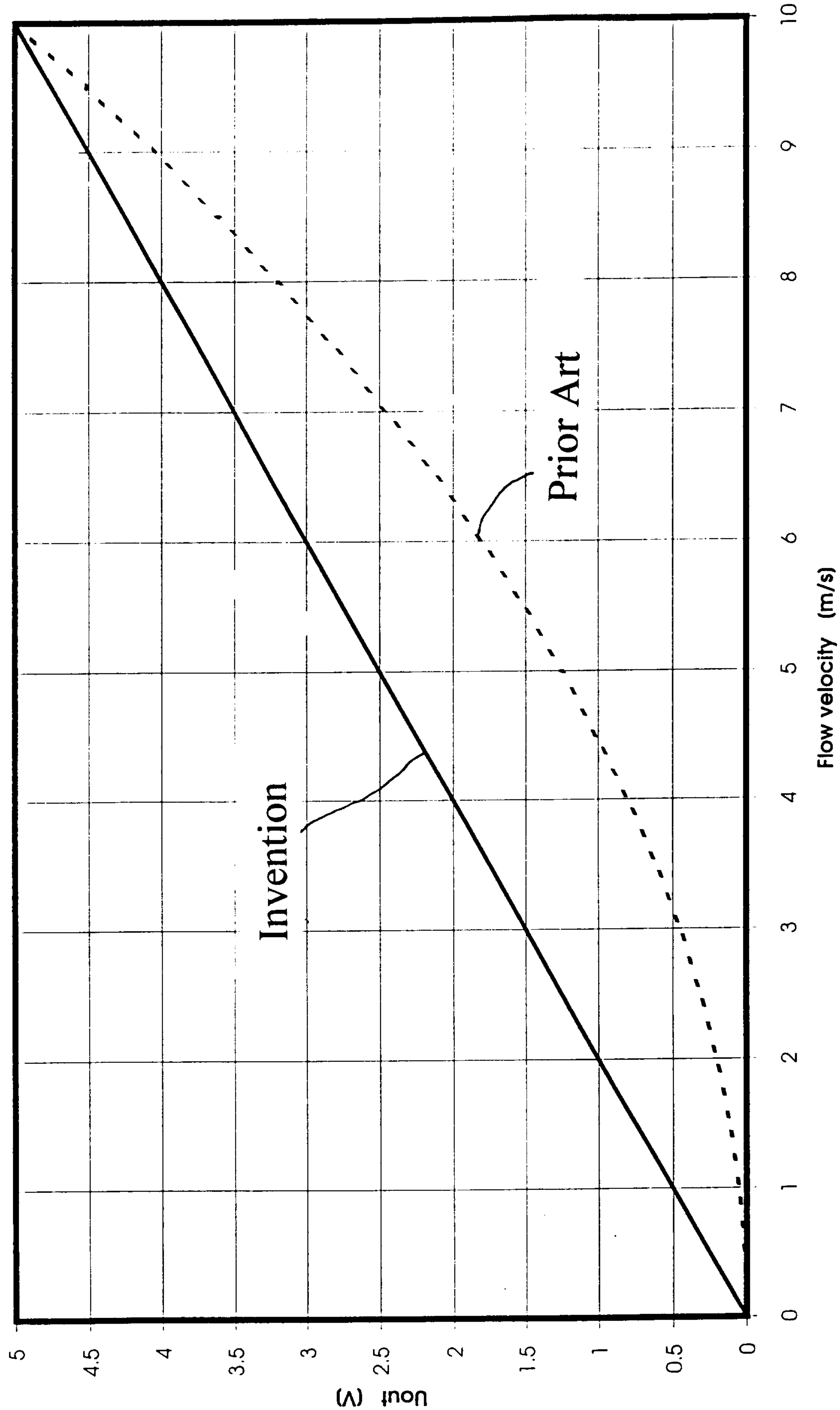


Fig. 11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2
2.5
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3.5
4
4.5
5
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1
2
3
4
5
6
7
8
9
10
Invention
Prior Art

Fig. 12